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Book of Abstracts
November 2-5, 1998

Kellie Ann Beall, Editor

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NUMERICAL STUDY OF THE NEAR-FIELD UNSTEADY DYNAMICS OF PLANAR PLUMES

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Introduction: Non-reacting buoyant plumes occur frequently in nature and in engineering practice, e.g. release of effluents from smokestacks, thermal plumes in the atmosphere, etc. Their dynamics are also known to exhibit similarities to those of pool fires [1-3]: In both cases the flow in the near-field of the source is characterized by large-scale coherent vortical structures that trace their origin to the buoyancy driven mechanism of vorticity generation. In the past, the study of buoyant plumes has, for the most part, been focused on the circular source case [e.g. 1-4]. Furthermore, the few studies dealing with the planar case have focused on the far-field dynamics [e.g. 5,6]. In this work we concentrate on the unsteady, near-field dynamics of planar plumes. The focus of the research lies in identifying the nature of the instabilities manifested in these flows. To this end, numerical simulations of the time-depended and un-averaged flow are performed. Numerical results are compared extensively with experimental evidence.

The numerical model: The unsteady two-dimensional buoyant motion of helium or of a helium-air mixture that flows from a nozzle into a stagnant atmosphere consisting of air at S.T.P. is considered. Isothermal conditions prevail. Two geometrical configurations are investigated. In both, the gravity vector is normal to the nozzle exit plane. In one of them, however, the nozzle is surrounded by a flat plate at the nozzle exit, while in the other the plate is removed and the nozzle is free-standing. These geometrical arrangements are assumed to distinguish plumes emanating from free-standing slots and from slots on the ground, respectively. Both helium and air are assumed to exhibit Newtonian-fluid and ideal-gas behavior, and to be essentially incompressible. The viscosity, μ, is assumed to be constant and the mass diffussivity, D, to vary according to $\rho D = \text{constant}$ where ρ is the mixture density. The governing equations (mass, momentum and species conservation equations coupled with the equation of state) are solved in non-primitive variable form. This involves the introduction of the vorticity, the streamfunction and of the gradients of the species mass-fractions.

The numerical solution is obtained using the Transport Element Method [7]. This *Lagrangian* methodology has its origins in the Vortex Element Method (VEM) [8] and is able to efficiently resolve the unsteady vortical flow and the coupled scalar fields. The numerical solution is initiated by discretizing the vorticity and the gradient of the scalar over a field of Lagrangian elements each of which is associated with a finite strength and a local distribution function. The velocity and scalar fields are obtained via convolutions over the elements. The time evolution of the flow and scalar fields, is accomplished via two-step local integration of the transport equations for each element.

Results: Comparison of the numerical results with experimental evidence indicates that the computational model is very effective in capturing the unsteady flow behavior. This can be witnessed qualitatively in Fig.1 where instantaneous experimental (left) and numerical (right) visualizations of the flow at similar parameters is shown. The figure makes evident that this flow is asymmetric about the nozzle centerline. Quantitative comparison between experiments and simulations is offered in Fig.2 where the frequencies of pulsation of the buoyant flow, i.e. the frequencies of the shedding of the vortical structures, are presented as a function of the Richardson number. The figure displays results for the nozzle-with-wall case. Results further indicate that the presence of the wall does not significantly affect the pulsation frequency. Transition from steady to pulsating behavior is also captured reasonably well by the simulations. Plumes emanating from a free-standing nozzle are more stable than those from a nozzle attached to horizontal wall. Despite the fact that the pulsation frequency varies weakly with the Richardson number, the instantaneous flow structure changes substantially as this parameter is varied. At relatively low Richardson number (weak buoyancy) the formation of the vortical structures occurs downstream, away from the nozzle, in a rather ordered, repeatable manner. Counter-rotating vortices form in a sequence resembling a Von-Karman street. At high Richardson number (strong buoyancy) the formation of the vortices occurs close to the nozzle exit forming the traditional mushroom structure characteristic of buoyant flows. Further downstream the flow becomes quite chaotic. In the experiments three-dimensionality ensues in this region. For intermediate values of the Richardson number the flow appears to alternate between the two extreme behaviors described above.

Future work: The mechanism of the instability will be probed in more detail assessing its origin and determining whether it may be characterized as absolute or convective. In addition, theoretical arguments will be developed to support the numerical-experimental findings described above.

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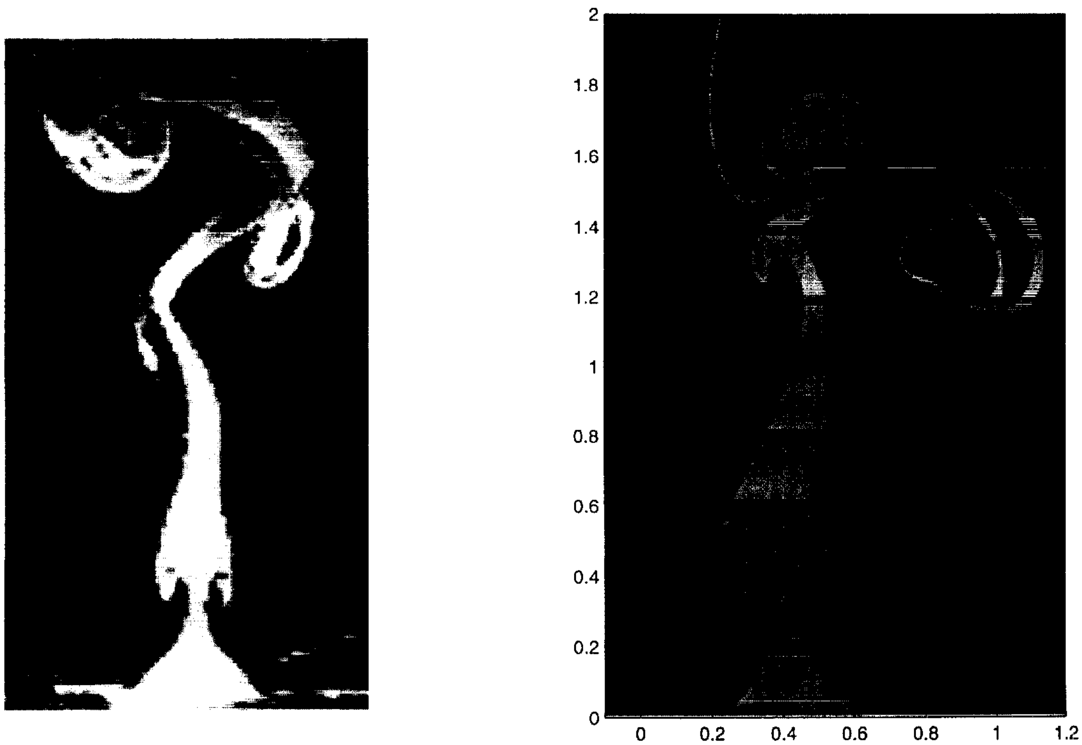

Figure 1. Experimental (left) and computational (right) instantaneous visualizations of the buoyant flow. Smoke seeded to the flow is displayed in gray-scale shades

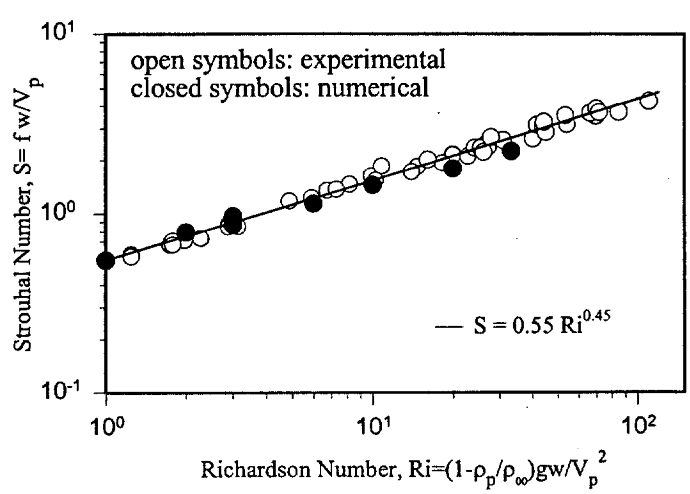

Figure 2. Correlation of the plume pulsation frequency in terms of the Strouhal and Richardson numbers. Comparison of experimental and numerical findings.